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(54) **METHODS AND APPARATUS FOR WIRELESS POWER AND COMMUNICATION TRANSFER**

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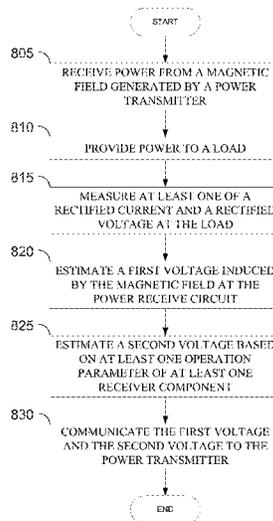*H02J 50/27* (2016.01)
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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,923,015 B2 12/2014 Madawala et al.
2013/0221913 A1 8/2013 Kim
(Continued)

FOREIGN PATENT DOCUMENTS

JP WO2014112019 * 7/2014
WO WO-2009065099 A2 5/2009
(Continued)

OTHER PUBLICATIONS

Lu X., et al., "Wireless Charging Technologies: Fundamentals, Standards, and Network Applications," IEEE Communications Surveys & Tutorials, 2015, pp. 1-41.
(Continued)

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(57) **ABSTRACT**

An aspect of this disclosure is an apparatus for receiving power wirelessly. The apparatus comprises a power receiver circuit that receives power from a magnetic field of a transmitter to provide to a load. At least one receiver component is coupled with the power receiver circuit and operates based on at least one operation parameter. A sensor measures at least one of a current and a voltage at the load. A controller estimates a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and the at least one operation parameter. The controller also estimates a second voltage based on the at least one operation parameter, the second voltage corresponding to a voltage at which the power receiver circuit operates with an efficiency level that exceeds a threshold efficiency. The communication circuit communicates the estimated voltages to the transmitter.

27 Claims, 7 Drawing Sheets

START

805 — RECEIVE POWER FROM A MAGNETIC FIELD GENERATED BY A POWER TRANSMITTER

810 — PROVIDE POWER TO A LOAD

815 — MEASURE AT LEAST ONE OF A RECTIFIED CURRENT AND A RECTIFIED VOLTAGE AT THE LOAD

820 — ESTIMATE A FIRST VOLTAGE INDUCED BY THE MAGNETIC FIELD AT THE POWER RECEIVE CIRCUIT

825 — ESTIMATE A SECOND VOLTAGE BASED ON AT LEAST ONE OPERATION PARAMETER OF AT LEAST ONE RECEIVER COMPONENT

830 — COMMUNICATE THE FIRST VOLTAGE AND THE SECOND VOLTAGE TO THE POWER TRANSMITTER

END

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    H02J 7/02   (2016.01)
    H02J 5/00   (2016.01)

(56)   **References Cited**

U.S. PATENT DOCUMENTS

2015/0077051 A1	3/2015	Kim et al.
2015/0303714 A1	10/2015	Keeling et al.
2016/0087476 A1	3/2016	Carobolante
2018/0034508 A1*	2/2018	Kim H04B 5/0037

FOREIGN PATENT DOCUMENTS

WO	WO-2014112019 A1	7/2014
WO	WO-2015144389 A1	10/2015

OTHER PUBLICATIONS

International Search Report and Written Opinion—PCT/US2017/045959—ISA/EPO—dated Oct. 23, 2017.
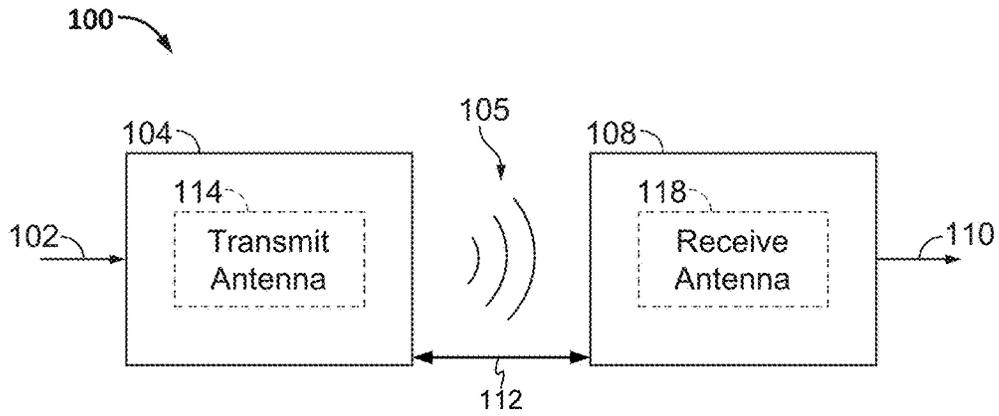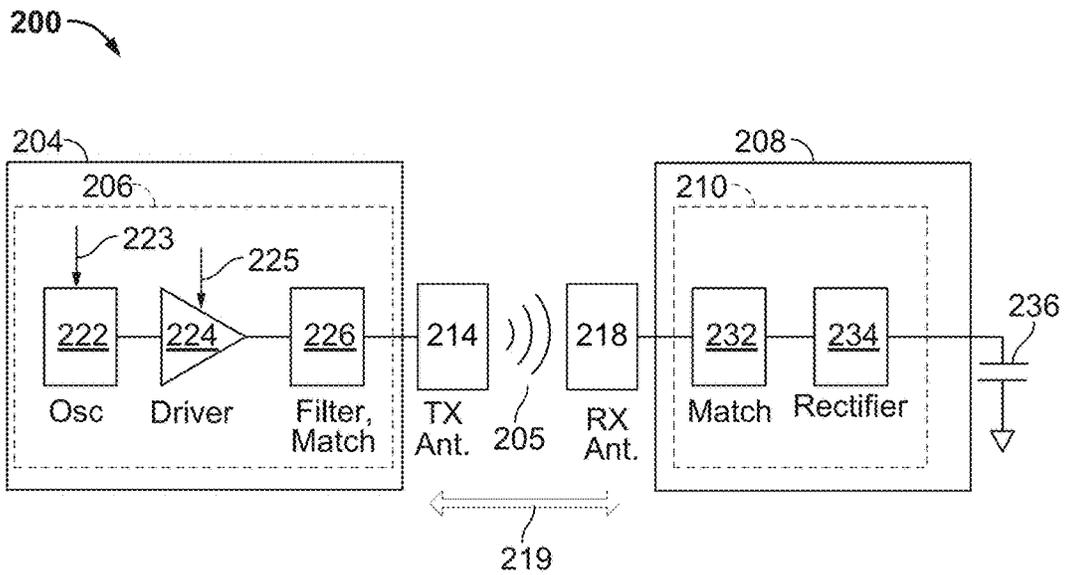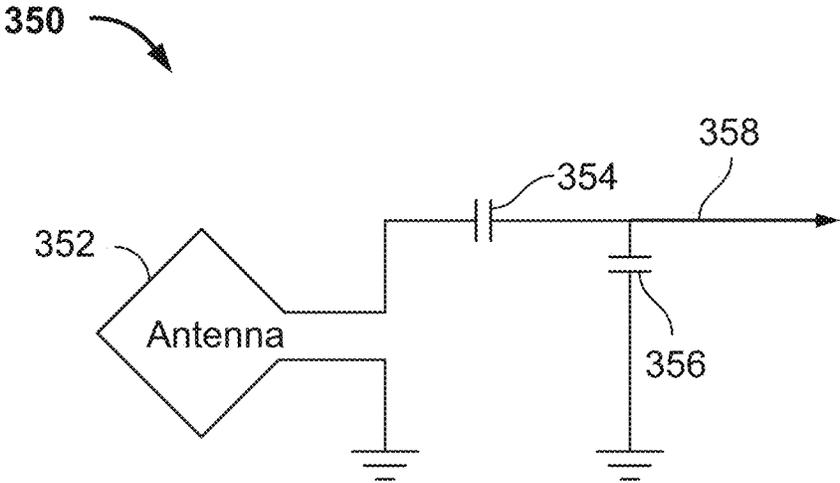
* cited by examiner

100

104

114

102

Transmit
Antenna

105

108

118

Receive
Antenna

110

112

FIG. 1

200

204

206

223

225

208

210

236

222

Osc

224

Driver

226

Filter,
Match

214

TX
Ant.

205

218

RX
Ant.

219

232

Match

234

Rectifier

FIG. 2

350

358

352   354

Antenna

356

FIG. 3

400

402

420 Memory

Controller

415

412 Oscillator

Vds

414 Driver

416 Filter

418 Matching Circuit

404 Transmit Antenna

FIG. 4

FIG. 5

FIG. 6

FIG. 7

START

805 — RECEIVE POWER FROM A MAGNETIC FIELD GENERATED BY A POWER TRANSMITTER

810 — PROVIDE POWER TO A LOAD

815 — MEASURE AT LEAST ONE OF A RECTIFIED CURRENT AND A RECTIFIED VOLTAGE AT THE LOAD

820 — ESTIMATE A FIRST VOLTAGE INDUCED BY THE MAGNETIC FIELD AT THE POWER RECEIVE CIRCUIT

825 — ESTIMATE A SECOND VOLTAGE BASED ON AT LEAST ONE OPERATION PARAMETER OF AT LEAST ONE RECEIVER COMPONENT

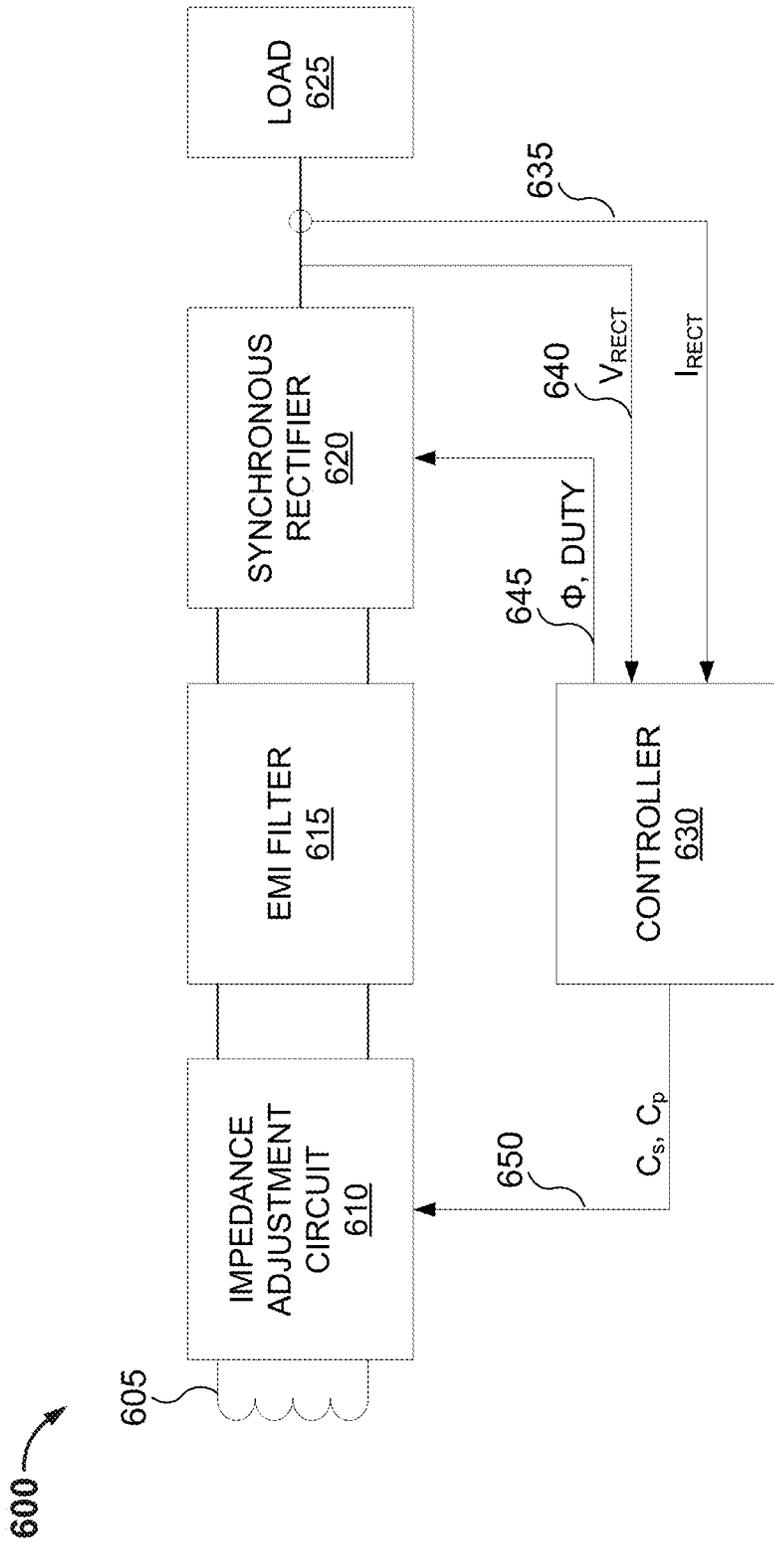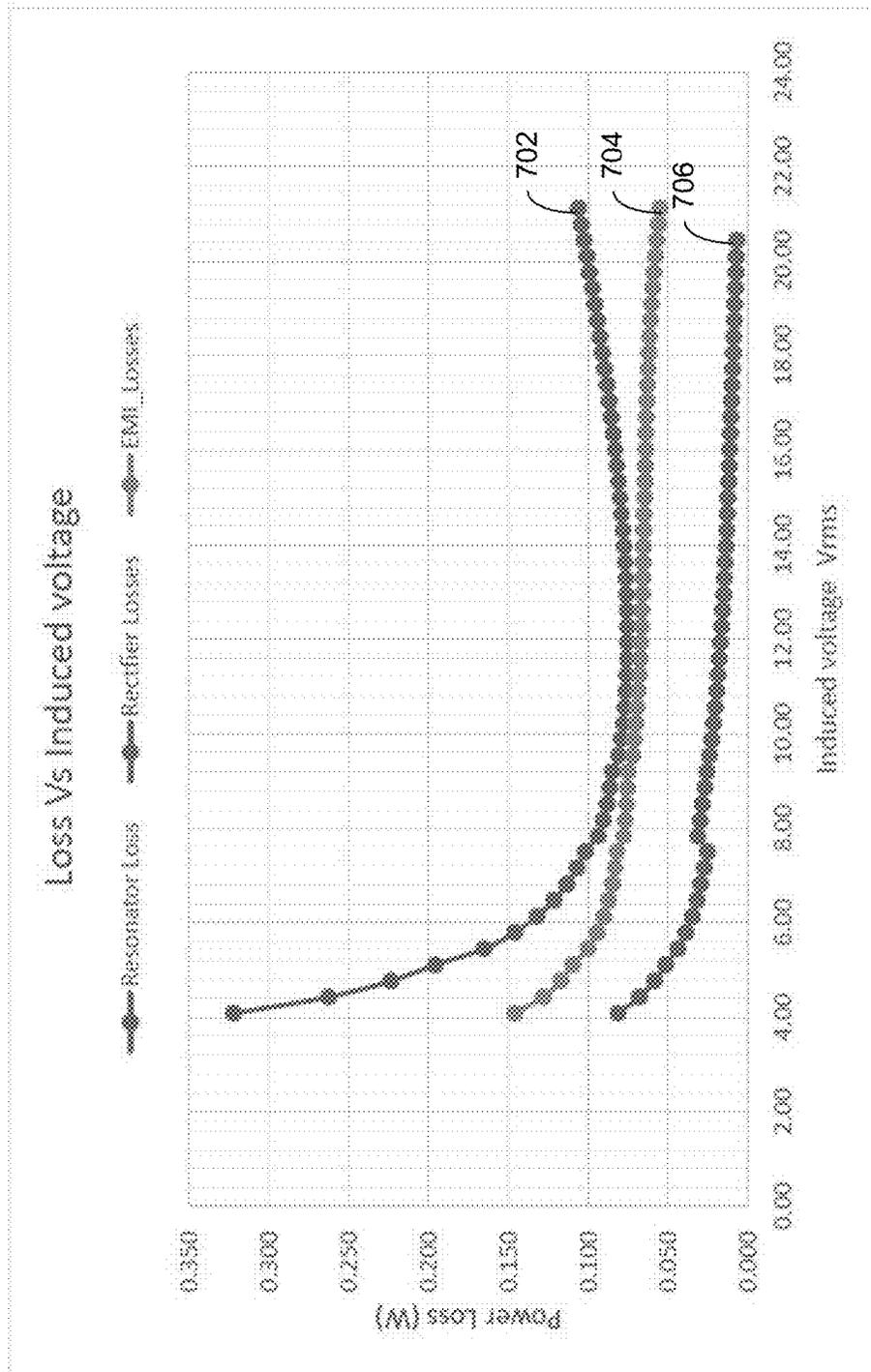830 — COMMUNICATE THE FIRST VOLTAGE AND THE SECOND VOLTAGE TO THE POWER TRANSMITTER
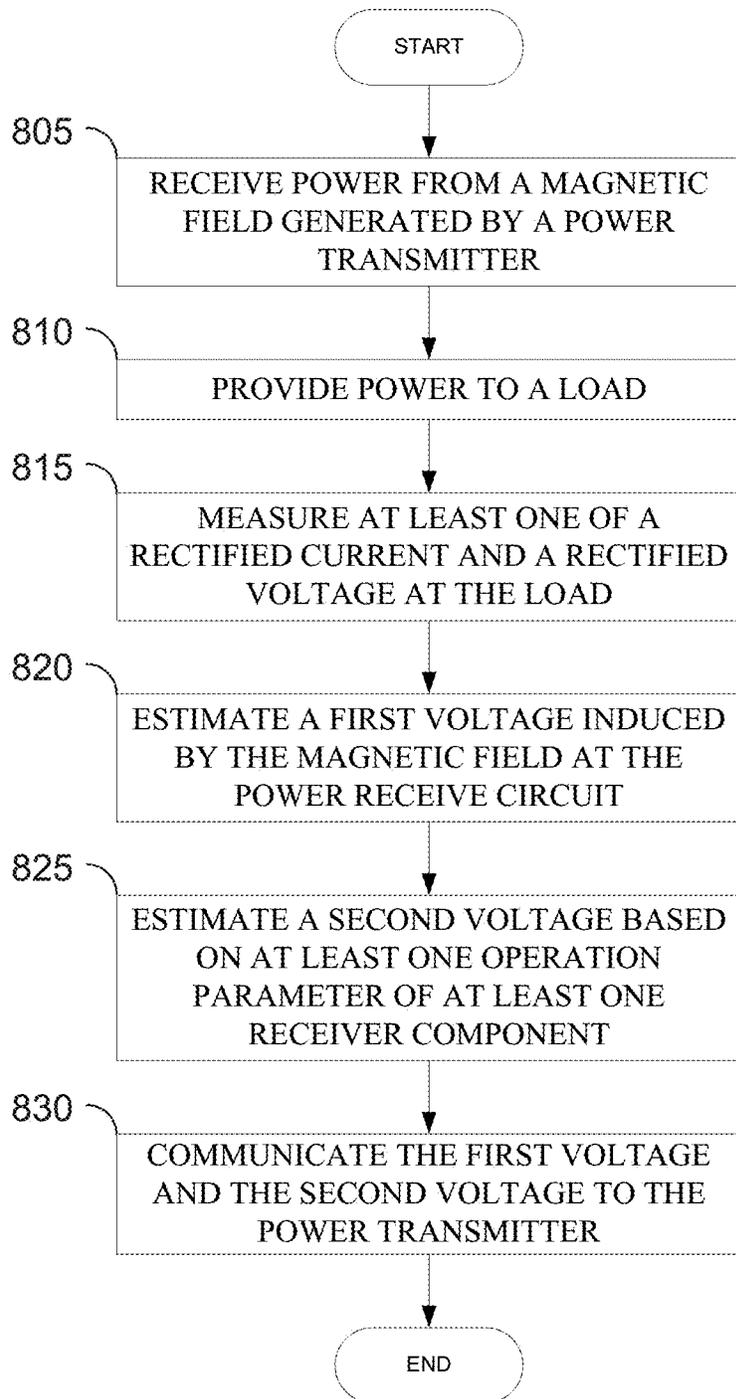
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FIG. 8

METHODS AND APPARATUS FOR WIRELESS POWER AND COMMUNICATION TRANSFER

BACKGROUND

Field of the Invention

The present disclosure relates generally to wireless power transfer. More specifically, this disclosure relates to methods and apparatus for controlling wireless power transfer between power transfer units and power receiving units to provide high efficiency power transfer.

Description of the Related Art

In general, a power transfer unit (PTU) wirelessly transmits power to a wireless receiving unit (PRU) via a wireless field generated by the PTU. In order to help ensure that the PRU receives sufficient magnetic field strength while staying within its design constraints and voltage withstanding capability, the PTU may receive one or more communications from the PRU relating to a rectified voltage at the PRU. The rectified voltage may correspond to the induced voltage received wirelessly at the PRU from the PTU that is being transferred to a load of the PRU. Accordingly, to make the wireless power transfer most efficient, the PTU adjusts its transmit current based on the received rectified voltage. The transmit current may be adjusted to change the wireless field such that the received rectified voltage approaches a target voltage at the PRU. Thus, to obtain the highest efficiency possible in the power transfer (e.g., to approach the target voltage), the rectified voltage as received from the PRU at the PTU must be indicative of the induced voltage received by the PRU. However, as PRUs become more involved or sophisticated, the rectified voltage becomes less useful as an actual measure of the induced voltage that is received by the PRU. Accordingly, alternate parameters are needed from the involved or sophisticated PRU that accurately represent the induced voltage received by the PRU so the PTU can adjust its transmit current and the wireless field to maximize power transfer efficiencies and to stay within design/spec constraints. Thus, there is a need for methods and apparatus for identifying the induced voltage at the PRU and providing it to the PTU.

SUMMARY

Various implementations of methods and devices within the scope of the appended claims each have several aspects, no single one of which is solely responsible for the desirable attributes described herein. Without limiting the scope of the appended claims, some prominent features are described herein.

An aspect of this disclosure is an apparatus for receiving power wirelessly. The apparatus comprises a power receiver circuit, at least one receiver component, at least one sensor, a controller, and a communication circuit. The power receiver circuit is configured to receive power from a magnetic field generated by a power transmitter and provide power to a load. The at least one receiver component is operationally coupled with the power receiver circuit and operating based, at least in part, on at least one operation parameter. The at least one sensor is configured to measure at least one of a current and a voltage at the load. The controller is configured to estimate a first voltage induced by the magnetic field at the power receiver circuit based on the at least one measured current and measured voltage and the at least one operation parameter of the at least one receiver component. The controller is also configured to estimate a

second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the power receiver circuit operates with an efficiency level that exceeds a threshold efficiency. The communication circuit is configured to communicate the first voltage and the second voltage to the power transmitter.

Another aspect of this disclosure is a method for receiving power wirelessly at a power receive unit. The method comprises receiving power, via a power receive circuit, from a magnetic field generated by a power transmit unit. The method further comprises providing power to a load and measuring at least one of a current and a voltage at the load. The method also comprises estimating a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and at least one operation parameter of at least one receiver component. The method further also comprises estimating a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the power receive circuit operates with an efficiency level that exceeds a threshold efficiency. The method also further comprises communicating the first voltage and the second voltage to the power transmit unit.

An additional aspect of this disclose is another apparatus for receiving power wirelessly. The apparatus comprises means for receiving power from a magnetic field generated by a power transmit unit and means for providing power to a load. The apparatus also comprises means for measuring at least one of a current and a voltage at the load. The apparatus further comprises means for estimating a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and at least one operation parameter of at least one receiver component. The apparatus also further comprises means for estimating a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the means for receiving power operates with an efficiency level that exceeds a threshold efficiency. The apparatus further also comprises means for communicating the first voltage and the second voltage to the power transmit unit.

BRIEF DESCRIPTION OF THE DRAWINGS

Details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings, and the claims.

FIG. 1 is a functional block diagram of a wireless power transfer system, in accordance with one exemplary implementation.

FIG. 2 is a functional block diagram of a wireless power transfer system, in accordance with another exemplary implementation.

FIG. 3 is a schematic diagram of a portion of transmit circuitry or receive circuitry of FIG. 2 including a transmit or receive antenna, in accordance with exemplary implementations.

FIG. 4 is a simplified functional block diagram of a transmitter that may be used in an inductive power transfer system, in accordance with exemplary implementations of the invention.

FIG. **5** is a simplified functional block diagram of a receiver that may be used in the inductive power transfer system, in accordance with exemplary implementations of the invention.

FIG. **6** is a simplified functional block diagram of a receiver configured to identify an induced voltage and a target induced voltage that may be used to improve wireless power transfer efficiencies in the inductive power transfer system, in accordance with exemplary implementations of the invention.

FIG. **7** is graph of power losses of the PRU (broken down into resonator losses, rectifier losses, and EMI filter losses) as a function of induced voltage, for a specific system state of the PRU, in accordance with exemplary implementations of the invention.

FIG. **8** is a flowchart includes a plurality of steps of a method of estimating an induced voltage and a target or optimal induced voltage of the receiver, in accordance with exemplary implementations of the invention.

The various features illustrated in the drawings may not be drawn to scale. Accordingly, the dimensions of the various features may be arbitrarily expanded or reduced for clarity. In addition, some of the drawings may not depict all of the components of a given system, method or device. Finally, like reference numerals may be used to denote like features throughout the specification and figures.

DETAILED DESCRIPTION

The detailed description set forth below in connection with the appended drawings is intended as a description of exemplary implementations and is not intended to represent the only implementations in which the invention may be practiced. The term "exemplary" used throughout this description means "serving as an example, instance, or illustration," and should not necessarily be construed as preferred or advantageous over other exemplary implementations. The detailed description includes specified details for the purpose of providing a thorough understanding of the exemplary implementations. In some instances, some devices are shown in block diagram form.

Wirelessly transferring power may refer to transferring any form of energy associated with electric fields, magnetic fields, electromagnetic fields, or otherwise from a transmitter to a receiver without the use of physical electrical conductors (e.g., power may be transferred through free space). The power output into a wireless field (e.g., a magnetic field) may be received, captured by, or coupled by a "receiving coil" to achieve power transfer.

FIG. **1** is a functional block diagram of a wireless power transfer system **100**, in accordance with one exemplary implementation. Input power **102** may be provided to a transmitter **104** from a power source (not shown) to generate a wireless (e.g., magnetic or electromagnetic) field **105** for performing wireless power transfer. A receiver **108** may couple to the wireless field **105** and generate output power **110** for storage or consumption by a device (not shown) coupled to the output power **110**. Both the transmitter **104** and the receiver **108** are separated by a distance **112**.

In one exemplary implementation, the transmitter **104** and the receiver **108** are configured according to a mutual resonant relationship. When the resonant frequency of the receiver **108** and the resonant frequency of the transmitter **104** are substantially the same or very close, transmission losses between the transmitter **104** and the receiver **108** are reduced. As such, wireless power transfer may be provided over a larger distance in contrast to purely inductive solu-

tions that may require large antenna coils which are very close (e.g., sometimes within millimeters). Resonant inductive coupling techniques may thus allow for improved efficiency and power transfer over various distances and with a variety of inductive coil configurations.

The receiver **108** may receive power when the receiver **108** is located in the wireless field **105** produced by the transmitter **104**. The wireless field **105** corresponds to a region where energy output by the transmitter **104** may be captured by the receiver **108**. The wireless field **105** may correspond to the "near-field" of the transmitter **104** as will be further described below. The wireless field **105** may also operate over a longer distance than is considered "near field." The transmitter **104** may include a transmit antenna **114** (e.g., a coil) for transmitting energy to the receiver **108**. The receiver **108** may include a receive antenna or coil **118** for receiving or capturing energy transmitted from the transmitter **104**. The near-field may correspond to a region in which there are strong reactance fields resulting from the currents and charges in the transmit antenna **114** that minimally radiate power away from the transmit antenna **114**. The near-field may correspond to a region that is within about one wavelength (or a fraction thereof) of the transmit antenna **114**.

FIG. **2** is a functional block diagram of a wireless power transfer system **200**, in accordance with another exemplary implementation. The system **200** includes a transmitter **204** and a receiver **208**. The transmitter **204** may include a transmit circuitry **206** that may include an oscillator **222**, a driver circuit **224**, and a filter and matching circuit **226**. The oscillator **222** may be configured to generate a signal at a desired or target frequency that may be adjusted in response to a frequency control signal **223**. The oscillator **222** may provide the oscillator signal to the driver circuit **224**. The driver circuit **224** may be configured to drive the transmit antenna **214** at, for example, a resonant frequency of the transmit antenna **214** based on an input voltage signal (V_D) **225**. The driver circuit **224** may be a switching amplifier configured to receive a square wave from the oscillator **222** and output a sine wave. For example, the driver circuit **224** may be a class E amplifier.

The filter and matching circuit **226** may filter out harmonics or other unwanted frequencies and match the impedance of the transmitter **204** to the impedance of the transmit antenna **214**. As a result of driving the transmit antenna **214**, the transmit antenna **214** may generate a wireless field **205** to wirelessly output power at a level sufficient for charging a battery **236**.

The receiver **208** may include a receive circuitry **210** that may include a matching circuit **232** and a rectifier circuit **234**. The matching circuit **232** may match the impedance of the receive circuitry **210** to the receive antenna **218**. The rectifier circuit **234** may generate a direct current (DC) power output from an alternate current (AC) power input to charge the battery **236**, as shown in FIG. **2**. The receiver **208** and the transmitter **204** may additionally communicate on a separate communication channel **219** (e.g., Bluetooth, ZigBee, cellular, etc.). The receiver **208** and the transmitter **204** may alternatively communicate via in-band signaling using characteristics of the wireless field **205**.

The receiver **208** may be configured to determine whether an amount of power transmitted by the transmitter **204** and received by the receiver **208** is appropriate for charging the battery **236**.

FIG. **3** is a schematic diagram of a portion of the transmit circuitry **206** or the receive circuitry **210** of FIG. **2** including a transmit or receive antenna, in accordance with exemplary

implementations. As illustrated in FIG. 3, a transmit or receive circuitry 350 may include an antenna 352. The antenna 352 may also be referred to or be configured as a "loop" antenna 352. The antenna 352 may also be referred to herein or be configured as a "magnetic" antenna or an induction coil. The term "antenna" generally refers to a component that may wirelessly output or receive energy for coupling to another "antenna." The antenna may also be referred to as a coil of a type that is configured to wirelessly output or receive power. As used herein, the antenna 352 is an example of a "power transfer component" of a type that is configured to wirelessly output and/or receive power.

The antenna 352 may include an air core or a physical core such as a ferrite core (not shown).

The transmit or receive circuitry 350 may form/include a resonant circuit. The resonant frequency of the loop or magnetic antennas is based on the inductance and capacitance. Inductance may be simply the inductance created by the antenna 352, whereas, capacitance may be added to the antenna's inductance to create a resonant structure at a desired or target resonant frequency. As a non-limiting example, a capacitor 354 and a capacitor 356 may be added to the transmit or receive circuitry 350 to create a resonant circuit. For a transmit circuitry, a signal 358 may be an input at a resonant frequency to cause the antenna 352 to generate a wireless field 105/205. For receive circuitry, the signal 358 may be an output to power or charge a load (not shown). For example, the load may comprise a wireless device configured to be charged by power received from the wireless field.

Other resonant circuits formed using other components are also possible. As another non-limiting example, a capacitor may be placed in parallel between the two terminals of the circuitry 350.

Referring to FIGS. 1 and 2, the transmitter 104/204 may output a time varying magnetic (or electromagnetic) field with a frequency corresponding to the resonant frequency of the transmit antenna 114/214. When the receiver 108/208 is within the wireless field 105/205, the time varying magnetic (or electromagnetic) field may induce a current in the receive antenna 118/218. As described above, if the receive antenna 118/218 is configured to resonate at the frequency of the transmit antenna 114/214, energy may be efficiently transferred. The AC signal induced in the receive antenna 118/218 may be rectified as described above to produce a DC signal that may be provided to charge or to power a load.

FIG. 4 is a simplified functional block diagram of a transmitter that may be used in an inductive power transfer system, in accordance with exemplary implementations of the invention. As shown in FIG. 4, the transmitter 400 includes transmit circuitry 402 and a transmit antenna 404 operably coupled to the transmit circuitry 402. The transmit antenna 404 may be configured as the transmit antenna 214 as described above in reference to FIG. 2. In some implementations, the transmit antenna 404 may be a coil (e.g., an induction coil). In some implementations, the transmit antenna 404 may be associated with a larger structure, such as a table, mat, lamp, or other stationary configuration. The transmit antenna 404 may be configured to generate an electromagnetic or magnetic field. In an exemplary implementation, the transmit antenna 404 may be configured to transmit power to a receiver device within a charging region at a power level sufficient to charge or power the receiver device.

The transmit circuitry 402 may receive power through a number of power sources (not shown). The transmit circuitry 402 may include various components configured to drive the transmit antenna 404. In some exemplary implementations,

the transmit circuitry 402 may be configured to adjust the transmission of wireless power based on the presence and constitution of the receiver devices as described herein. As such, the transmitter 400 may provide wireless power efficiently and safely.

The transmit circuitry 402 may further include a controller 415. In some implementations, the controller 415 may be a micro-controller. In other implementations, the controller 415 may be implemented as an application-specified integrated circuit (ASIC). The controller 415 may be operably connected, directly or indirectly, to each component of the transmit circuitry 402. The controller 415 may be further configured to receive information from each of the components of the transmit circuitry 402 and perform calculations based on the received information. The controller 415 may be configured to generate control signals for each of the components that may adjust the operation of that component. As such, the controller 415 may be configured to adjust the power transfer based on a result of the calculations performed by it.

The transmit circuitry 402 may further include a memory 420 operably connected to the controller 415. The memory 420 may comprise random-access memory (RAM), electrically erasable programmable read only memory (EE-PROM), flash memory, or non-volatile RAM. The memory 420 may be configured to temporarily or permanently store data for use in read and write operations performed by the controller 415. For example, the memory 420 may be configured to store data generated as a result of the calculations of the controller 415. As such, the memory 420 allows the controller 415 to adjust the transmit circuitry 402 based on changes in the data over time.

The transmit circuitry 402 may further include an oscillator 412 operably connected to the controller 415. The oscillator 412 may be configured as the oscillator 222 as described above in reference to FIG. 2. The oscillator 412 may be configured to generate an oscillating signal (e.g., radio frequency (RF) signal) at the operating frequency of the wireless power transfer. In some exemplary implementations, the oscillator 412 may be configured to operate at the 6.78 MHz ISM frequency band. The controller 415 may be configured to selectively enable the oscillator 412 during a transmit phase (or duty cycle). The controller 415 may be further configured to adjust the frequency or a phase of the oscillator 412 which may reduce out-of-band emissions, especially when transitioning from one frequency to another. As described above, the transmit circuitry 402 may be configured to provide an amount of power to the transmit antenna 404, which may generate energy (e.g., magnetic flux) about the transmit antenna 404.

The transmit circuitry 402 may further include a driver circuit 414 operably connected to the controller 415 and the oscillator 412. The driver circuit 414 may be configured as the driver circuit 224 as described above in reference to FIG. 2. The driver circuit 414 may be configured to drive the signals received from the oscillator 412, as described above.

The transmit circuitry 402 may further include a low pass filter (LPF) 416 operably connected to the transmit antenna 404. The low pass filter 416 may be configured as the filter portion of the filter and matching circuit 226 as described above in reference to FIG. 2. In some exemplary implementations, the low pass filter 416 may be configured to receive and filter an analog signal of current and an analog signal of voltage generated by the driver circuit 414. The analog signal of current may comprise a time-varying current signal, while the analog signal of current may comprise a time-varying voltage signal. In some implementations, the

low pass filter 416 may alter a phase of the analog signals. The low pass filter 416 may cause the same amount of phase change for both the current and the voltage, canceling out the changes. In some implementations, the controller 415 may be configured to compensate for the phase change caused by the low pass filter 416. The low pass filter 416 may be configured to reduce harmonic emissions to levels that may prevent self-jamming. Other exemplary implementations may include different filter topologies, such as notch filters that attenuate specified frequencies while passing others.

The transmit circuitry 402 may further include a fixed impedance matching circuit 418 operably connected to the low pass filter 416 and the transmit antenna 404. The matching circuit 418 may be configured as the matching portion of the filter and matching circuit 226 as described above in reference to FIG. 2. The matching circuit 418 may be configured to match the impedance of the transmit circuitry 402 (e.g., 50 ohms) to the transmit antenna 404. Other exemplary implementations may include an adaptive impedance match that may be varied based on measurable transmit metrics, such as the measured output power to the transmit antenna 404 or a DC current of the driver circuit 414. The transmit circuitry 402 may further comprise discrete devices, discrete circuits, and/or an integrated assembly of components.

Transmit antenna 404 may be implemented as an antenna strip with the thickness, width and metal type selected to keep resistance losses low.

FIG. 5 is a block diagram of a receiver, in accordance with an implementation of the present invention. As shown in FIG. 5, a receiver 500 includes a receive circuitry 502, a receive antenna 504, and a load 550. The receiver 500 further couples to the load 550 for providing received power thereto. Receiver 500 is illustrated as being external to device acting as the load 550 but may be integrated into load 550. The receive antenna 504 may be operably connected to the receive circuitry 502. The receive antenna 504 may be configured as the receive antenna 218 as described above in reference to FIG. 2. In some implementations, the receive antenna 504 may be tuned to resonate at a frequency similar to a resonant frequency of the transmit antenna 404, or within a specified range of frequencies, as described above. The receive antenna 504 may be similarly dimensioned with transmit antenna 404 or may be differently sized based upon the dimensions of the load 550. The receive antenna 504 may be configured to couple to the magnetic field generated by the transmit antenna 404, as described above, and provide an amount of received energy to the receive circuitry 502 to power or charge the load 550.

The receive circuitry 502 may be operably coupled to the receive antenna 504 and the load 550. The receive circuitry may be configured as the receive circuitry 210 as described above in reference to FIG. 2. The receive circuitry 502 may be configured to match an impedance of the receive antenna 504, which may provide efficient reception of wireless power. The receive circuitry 502 may be configured to generate power based on the energy received from the receive antenna 504. The receive circuitry 502 may be configured to provide the generated power to the load 550. In some implementations, the receiver 500 may be configured to transmit a signal to the transmitter 400 indicating an amount of power received from the transmitter 400.

The receive circuitry 502 may include a processor-signaling controller 516 configured to coordinate the processes of the receiver 500 described below.

The receive circuitry 502 provides an impedance match to the receive antenna 504. The receive circuitry 502 includes power conversion circuitry 506 for converting a received energy into charging power for use by the load 550. The power conversion circuitry 506 includes an AC-to-DC converter 508 coupled to a DC-to-DC converter 510. The AC-to-DC converter 508 rectifies the AC energy signal received at the receive antenna 504 into a non-alternating power while the DC-to-DC converter 510 converts the rectified AC energy signal into an energy potential (e.g., voltage) that is compatible with the load 550. Various AC-to-DC converters are contemplated including partial and full rectifiers, regulators, bridges, doublers, as well as linear and switching converters.

The receive circuitry 502 may further include a matching circuit 512. The matching circuit 512 may comprise one or more resonant capacitors in either a shunt or a series configuration. In some implementations these resonant capacitors may tune the receive antenna to a specific frequency or to a specific frequency range (e.g., a resonant frequency).

The load 550 may be operably connected to the receive circuitry 502. The load 550 may be configured as the battery 236 as described above in reference to FIG. 2. In some implementations the load 550 may be external to the receive circuitry 502. In other implementations the load 550 may be integrated into the receive circuitry 502.

In wireless transfer systems, the wireless transfer of power between a power transfer unit (PTU) 400 (e.g., the transmitter 400 of FIG. 4) and a power receive unit (PRU) 500 (e.g., the receiver 500 of FIG. 5) is directly controlled by a transmit current that feeds the PTU's antenna (e.g., antenna 404). Based on the transmit current of the PTU 400, a magnetic field having a magnetic field strength is generated by the PTU's antenna 404. This magnetic field strength determines, at least in part, the voltage induced at the PRU 500. In some implementations, for example implementations involving unsophisticated PRUs 500, the estimated voltage induced at the PRU 500 corresponds to a measured rectified voltage (V_{rect}). Accordingly, the measured V_{rect} may be communicated to the PTU 400 to allow the PTU 400 to control its transmit current to adjust the V_{rect} to a desired or target voltage. In some implementations, the target voltage will maximize power transfer efficiency. The target voltage may be a desired voltage, a threshold voltage, a user set voltage, and/or an optimal voltage. Based on the reporting of the V_{rect} from the PRU 500 to the PTU 400 and the PTU's adjustment of its transmit current based on the reported V_{rect}, ideal operating points between the two devices (and/or between the PTU and multiple PRUs) can be tracked and maintained over time.

However, in implementations where the PRU 500 is involved or sophisticated, the V_{rect} may not be an accurate measure of the most efficient or target voltage. For example, in some implementations, the involved or sophisticated PRU 500 comprises a dynamically adjustable rectifier circuit that includes various components (e.g., a voltage doubler, a full-bridge rectifier, one or more tuning capacitors or inductors, etc.) that change the V_{rect}. Accordingly, the V_{rect} alone may not necessarily be indicative of or directly associated with the voltage induced by the magnetic field at the PRU 500. For example, based on added components and complexity of the PRU 500, the V_{rect} as measured and reported by the PRU 500 may be constant over a range of magnetic fields, even if the PRU 500 is not operating at an efficient level or within its designed operating voltage range. Accordingly, the reporting of the V_{rect} from the PRU 500 to the PTU

400 and the PTU's adjustment of its transmit current based on the reported V_{rect} may no longer ensure that power transfer at ideal operating points between the two devices can be tracked and maintained over time.

Alternatively, in some implementations, it is desirable to measure or determine additional and/or different values by the PRU **500** and report them to the PTU **400**. In some implementations, the PRU **500** reports these additional and/or different values directly to the PTU **400** to determine the ideal transmit current. For example, the PRU **500** communicates an induced voltage and/or a target induced voltage to the PTU **400** via a communication channel (e.g., Bluetooth, inband signaling, etc.). In some implementations, the PRU **500** "translates or associates these additional and/or different values with different V_{rect} values for reporting to the PTU **400**. For example, the PRU **500** associates a determined induced voltage or target induced voltage with a V_{rect} that the PRU **500** knows will cause the PTU **400** to adjust its transmit current to a specific level and cause a known change to the induced voltage at the PRU **500**. The PRU **500** may also convert the estimated induced voltage and the estimated target induced voltage to a V_{rect} value (or another format understood by PTUs **400**). By being able to convert the determined induced voltage or target induced voltage to a V_{rect}, the PRU **500** may maintain interoperability with PTUs **400** configured to receive V_{rect} values for optimizing power transfer efficiencies. In some implementations, the induced voltage may correspond to an open circuit voltage as seen by the receive antenna **504** of the PRU **500**

Thus, in implementations of PRUs **500** without dynamic tuning or voltage modifying components, the measured V_{rect} is a function of the induced voltage EMF and can be used to regulate the PTU's transmit current, as described above. In implementations of PRUs **500** having dynamic tuning and/ or a controlled synchronous rectifier, the V_{rect} alone is not sufficient to regulate the induced voltage EMF.

FIG. **6** is a simplified functional block diagram of a receiver (PRU) **600** configured to identify an induced voltage and a target induced voltage (e.g., operation parameters) that may be used to improve wireless power transfer efficiencies and ensure standards compliance in the inductive power transfer system, in accordance with exemplary implementations of the invention. The PRU **600** may be configured to identify and/or estimate an induced voltage at the PRU **600** that corresponds to the magnetic field generated by the PTU (not shown in this figure). The PRU **600** comprises an antenna **605**, an impedance adjustment circuit **610**, an electromagnetic interference ("EMI") filter **615**, a synchronous rectifier **620**, a load **625**, and a controller **630**. Additionally, the PRU **600** may include an I_{rect} signal **635** (between the controller **630** and an input of the load **625** or output of the synchronous rectifier **620**) and a V_{rect} signal **640** (also between the controller **630** and the input of the load **625** or output of the synchronous rectifier **620**). The PRU **000** also includes a phase (Φ) and duty signal **645** between the controller **630** and the synchronous rectifier and a series and shunt capacitance signal **650** between the controller and the impedance adjustment circuit **610**. In some implementations, the I_{rect} and V_{rect} measurements may be performed by one or more sensors or other components configured to measure current and/or voltage at various locations in the PRU **600**.

The antenna **605** of the PRU **600** may wirelessly receive power via the magnetic field (not shown in this figure). The magnetic field may generate an induced voltage in the antenna **605** when it is exposed to the magnetic field. The

antenna **605** is coupled to the impedance adjustment circuit **610** such that the induced voltage is an input of the impedance adjustment circuit **610**. The impedance adjustment circuit **610** may dynamically adjust an impedance, Z, of the PRU **600** as seen by the PTU (for example, by adjusting one or both of a reactance component, X, and a resistance component, R, of the impedance, Z, of the PRU **600**). In some implementations, the voltage at the output of the impedance adjustment circuit **610** is or is not directly associated with the transmit current of the PTU and the generated magnetic field strength. In some implementations, the controller **630** provides one or more inputs to the impedance adjustment circuit **610**, according to which the impedance adjustment circuit **610** may adjust the impedance, Z, of the PRU **600**.

The impedance adjustment circuit **610** may be further coupled to the EMI filter **615**. The EMI filter **615** may be configured to suppress and/or reduce interference. The EMI filter **615** may generate a filtered voltage that is output to the synchronous rectifier **620** coupled to the EMI filter **615**. The synchronous rectifier **620** may be configured to rectify the filtered voltage received from the EMI filter **615**. The synchronous rectifier **620** may be more efficient than passive rectifiers. In some implementations, the synchronous rectifier **620** receives one or more inputs from the controller **630**. In some implementations, the controller **630** provides one or more inputs to the synchronous rectifier **620**, according to which the synchronous rectifier **620** may adjust a rectification of the PRU **600**. While controlling the synchronous rectifier **620** may not impact induced voltage, adjusting the synchronous rectifier **620** may directly impact an output voltage of the synchronous rectifier **620** (e.g., V_{rect}) and may impact an effective impedance of the synchronous rectifier **620**. The effective impedance of the synchronous rectifier **620** may impact the impedance of the PRU **600** as well as an efficiency of the PRU **600**. Accordingly, the synchronous rectifier **620** can be used as a dynamic tuning element to keep V_{rect} within a certain range, improve system efficiency, etc. The output of the synchronous rectifier **620** is directed to the load **625**. In some implementations, the output of the synchronous rectifier **620** is a voltage for charging and or powering the load **625**. The load **625**, in some implementations, comprises a battery or other energy storage device or a component that is powered by the rectified voltage received from the synchronous rectifier **620**.

In some implementations, the impedance adjustment circuit **610** and/or the synchronous rectifier **620** may be referred to as receiver components. Receiver components may comprise any component(s) that varies or modulates the induced voltage to generate the rectified DC voltage provided to the load **625**. For example, the receiver components may include individual capacitors or inductors or circuits comprising multiple individual components. In some implementations, the receiver component(s) are characterized by one or more characteristics or parameters that affect or control performance of the receiver component(s) (e.g., set points or control variables, etc.). For example, when the receiver component is a capacitor, the receiver component may be characterized by a capacitance value. Similarly, when the receive component is the impedance adjustment circuit **610** or the synchronous rectifier **620**, the receiver component may be characterized by capacitance or phase and duty values, respectively. These parameters may be controlled by the controller **630** and/or may be used in calculations (e.g., as inputs) as described below.

The controller **630** may be configured to control one or more components of the PRU **600** and perform one or more

voltage determination or identifications at the PRU **600**. In some implementations, the controller **630** receives one or more "inputs" from one or more components or points of the PRU **600**. The inputs may receive values or measurements received from other components of the PRU **600** (e.g., the receiver components) and may receive set points and/or control variables established by the controller **630**. For example, the one or more values or measurements comprise voltage and current measurements (e.g., V_{rect} and I_{rect} measurements). In some implementations, the controller **630** may measure or receive the measurements of the I_{rect} and V_{rect} via the signals **635** and **640**, respectively. In some implementations, the I_{rect} and V_{rect} measurements may be performed by one or more sensors or other components configured to measure current and/or voltage at various locations in the PRU **600**, where the signals **635** and **640** are received by the controller **630** from the one or more sensors. The set points and/or system control variables (e.g., phase and duty cycle of rectifier controlled rectifiers and tuning variables of series and/or shunt tuning capacitors) may be set points and system control variables that are controlled by the controller **630** itself and set via the signal **645** to the synchronous rectifier **620** and signal **650** to the impedance adjustment circuit **610**.

Based on these inputs, the controller **630** may estimate an induced voltage (or electromotive force EMF_{FB}), which may correspond to the induced voltage of the PRU. In some implementations, the EMF_{FB} may be determined using Equation 1:

$$EMF_{FB}=w*M*I_{tx} \qquad \text{(Equation 1)}$$

where:
  w=frequency, in hertz (Hz);
  M=mutual inductance, in henry (H); and
  I_{tx}=the transmit current at the PTU, in amps (A).
In some implementations, the induced voltage EMF_{FB} is based, at least in part, on a location of the PRU **600** in the generated magnetic field (e.g., a position or location of the PRU **600** on a charging surface of the PTU) and the transmit current of the PTU. In some implementations, the EMF_{FB} as determined by the PRU **600** is scaled as needed and, thus, replaces V_{rect} when used with existing PTU control mechanisms.

In some implementations, the controller **630** comprises at least one estimator that is used to estimate the induced voltage EMF_{FB} based on the identified inputs. In some implementations, the estimator uses one or more estimation models to predict the induced voltage EMF_{FB} based on the inputs. A non-exhaustive list of exemplary estimation models is provided below.

A first estimator of the controller **630** may comprise a multi-variable curve fit estimator model based on simulation data or hardware prototype measurements. The curve fit model may generate an equation that is based on particular hardware or a component of the PRU **600**. For example, the multi-variable curve fit estimator model may be based on a simulation of a dynamically tuned PRU **600** (e g, a dynamically tuned impedance adjustment circuit **610** or a controlled synchronous rectifier **620**). For example, Equation 2 below is an example of a curve fit model for a dynamically tuned PRU **600**:

$$EMF_{FB}=2.93436+0.010181*C_p+0.200956*V_{rect}+ \\ 0.672261*I_{rect} \qquad \text{(Equation 2)}$$

where:
  C_p=a shunt dynamic capacitance of the impedance adjustment circuit **610**, Pico farads (pF);

  V_{rect} rectified voltage at the output of the synchronous rectifier **620** transferred to the load **625**, in volts (V); and

  I_{rect}=current at the output of the synchronous rectifier **620**, in amps (A)

Simulation data used to generate the curve fit model of Equation 2 is shown in Table 1 below. In some embodiments, other methods may be used to generate the curve fit model of Equation 2, such as a dynamically operated simulation, measurements from a prototype, etc. Accordingly, contrary estimated the induced voltage of the PRU purely by measuring the V_{rect} as discussed above in relation to unsophisticated PRUs, the controller **630** estimates the induced voltage of the PRU by including various parameters of the receiver components. For example, for the PRU **600** shown in FIG. **6**, the controller **630** may utilize parameters from the impedance adjustment circuit **610** and the synchronous rectifier **620** along with the measured V_{rect} and I_{rect} to estimate the induced voltage at the PRU **600**. Thus, the estimated induced voltage for the sophisticated PRU **600** is more accurate due to the inclusion of a larger number of variables in the estimation equation.

TABLE 1

| | | Data to Generate Equation 2 | | |
Cp	Vrect	Irect	Actual EMF	Predicted EMF (EMFFB)
183.33	3.00	2.50	6.95	7.09
183.33	3.50	2.34	6.95	7.07
183.33	4.00	2.16	6.95	7.06
195.67	3.00	3.13	6.95	7.64
195.67	3.50	2.91	6.95	7.59
195.67	4.00	2.69	6.95	7.54
208.00	3.00	3.35	6.95	7.90
208.00	3.50	3.13	6.95	7.86
208.00	4.00	2.91	6.95	7.81
220.33	3.00	2.90	6.95	7.73
220.33	3.50	2.75	6.95	7.73
220.33	4.00	2.60	6.95	7.73
232.67	3.00	2.32	6.95	7.47
232.67	3.50	2.24	6.95	7.51
232.67	4.00	2.15	6.95	7.55
245.00	3.00	1.88	6.95	7.29
245.00	3.50	1.82	6.95	7.36
245.00	4.00	1.77	6.95	7.42
183.33	3.00	2.30	7.53	7.28
183.33	3.50	2.63	7.53	7.27
183.33	4.00	2.46	7.53	7.26
195.67	3.00	3.51	7.53	7.89
195.67	3.50	3.29	7.53	7.84
195.67	4.00	3.07	7.53	7.79
208.00	3.00	3.74	7.53	8.17
208.00	3.50	3.52	7.53	8.12
208.00	4.00	3.30	7.53	8.07
220.33	3.00	3.21	7.53	7.94
220.33	3.50	3.07	7.53	7.94
220.33	4.00	2.92	7.53	7.94
232.67	3.00	2.56	7.53	7.63
232.67	3.50	2.47	7.53	7.67
232.67	4.00	2.39	7.53	7.71
245.00	3.00	2.06	7.53	7.42
245.00	3.50	2.01	7.53	7.48
245.00	4.00	1.95	7.53	7.54
183.33	3.00	3.09	8.11	7.48
183.33	3.50	2.92	8.11	7.47
183.33	4.00	2.76	8.11	7.46

Equation 3 below is an example of a curve fit model for a PRU **600** utilizing a controlled synchronous rectifier:

$$EMF_{FB}=-0.233096+0.113718*Phase+ \\ 0.798436*V_{rect}+9.17238*I_{rect} \qquad \text{(Equation 3)}$$

where:

Phase=a phase difference between an AC input waveform at the synchronous rectifier **620** and a firing angle for the switches of the synchronous rectifier **620** (for example, an ideal rectifier may operate with zero phase, where the phase can be adjusted to achieve other goals);

V_{rect}=rectified voltage at the output of the synchronous rectifier **620** transferred to the load **625**; and

I_{rect}=current at the output of the synchronous rectifier **620**

Simulation data used to generate the curve fit model of Equation 3 is shown in Table 2 below. In some embodiments, other methods may be used to generate the curve fit model of Equation 3, such as a dynamically operated simulation, measurements from a prototype, etc.

TABLE 2

Data to Generate Equation 3				
Phase	Vrect	Irect	Actual EMF	Predicted EMF (EMFFB)
12.50	3.00	0.37	6.95	7.52
12.50	3.50	0.33	6.95	7.52
12.50	4.00	0.29	6.95	7.54
10.00	3.00	0.41	6.95	7.61
10.00	3.50	0.37	6.95	7.61
10.00	4.00	0.32	6.95	7.59
7.50	3.00	0.45	6.95	7.68
7.50	3.50	0.41	6.95	7.68
7.50	4.00	0.36	6.95	7.64
5.00	3.00	0.49	6.95	7.70
5.00	3.50	0.44	6.95	7.68
5.00	4.00	0.39	6.95	7.64
2.50	3.00	0.50	6.95	7.55
2.50	3.50	0.45	6.95	7.53
2.50	4.00	0.40	6.95	7.47
0.00	3.00	0.51	6.95	7.36
0.00	3.50	0.46	6.95	7.33
0.00	4.00	0.41	6.95	7.27
12.50	3.00	0.42	7.53	7.99
12.50	3.50	0.39	7.53	8.03
12.50	4.00	0.34	7.53	8.01
10.00	3.00	0.47	7.53	8.13
10.00	3.50	0.43	7.53	8.15
10.00	4.00	0.38	7.53	8.13
7.50	3.00	0.51	7.53	8.24
7.50	3.50	0.47	7.53	8.25
7.50	4.00	0.43	7.53	8.24
5.00	3.00	0.55	7.53	8.27
5.00	3.50	0.50	7.53	8.27
5.00	4.00	0.46	7.53	8.25
2.50	3.00	0.56	7.53	8.13
2.50	3.50	0.52	7.53	8.13
2.50	4.00	0.47	7.53	8.10
0.00	3.00	0.57	7.53	7.95
0.00	3.50	0.53	7.53	7.94
0.00	4.00	0.48	7.53	7.90
12.50	3.00	0.47	8.11	8.44
12.50	3.50	0.44	8.11	8.50
12.50	4.00	0.39	8.11	8.51

Thus, a curve fit model equation may be developed for any configuration of the PRU **600**. In some implementations, more complicated polynomials may be used to implement the curve fit model as required—the polynomial will model the physical relationships.

The curve fit estimator model may be advantageous as an estimator because it is agnostic to specific system states and/or modes of the PRU **600**. For example, the curve fit estimator may be capable of predicting induced voltages EMF_{FB} over an entire range of PRU system states (e.g., voltages, currents, dynamic capacitances, etc.). Additionally, the curve fit estimator model may be configured to include load power compensation, thereby accounting for voltage

drops, impacts on tunings due to load changes, etc. Furthermore, overvoltage conditions can be better defined using the curve fit estimator models and estimated induced voltage (EMF_{FB}) and a state of the system control variables (e.g., maximum de-tuning). Adjusting the I_{tx} based on the V_{rect} as compared to the EMF_{FB} and EMF_{SET} adjustment as described herein, is load dependent (e.g., dependent on a battery, or other load of the PRU **600**). The V_{rect} being load dependent means that the reported V_{rect} can fluctuate based on an amount of power delivered by the PRU **600** to its load. The EMF_{FB} method may address this by providing an estimated induced EMF_{FB} based on one or more variables that reflect a current state of the PRU **600**, which may impact the induced EMF_{FB}. The curve fit estimator model may also allow for a reduction of memory otherwise used for storage of interpolated data.

More generally, one example of a broader covering equation may be seen in Equation 4 below. Equation 4 shows that the estimated induced voltage may be a sum of rectified voltages, rectified currents, variable reactance and/or impedance values, and rectifier phase control values. For example, where the PRU **600** comprises both the dynamically tuned impedance adjustment circuits **610** and the controlled synchronous rectifier **620**, estimated induced voltage may comprise load DC voltage and current, reactance of the impedance adjustment circuit **610** and phase of the controlled synchronous rectifier **620**. For example, the estimated induced voltage be a sum of V_{rect}, I_{rect}, reactance, phase and duty (not shown) components of the PRU implementation. Generic equation

$$EMF_{FB}=[i_0V_{rect}+i_1V_{rect}^2+\ldots i_nV_{rect}^n]+[j_0I_{rect}+$$
$$j_1I_{rect}^2+\ldots j_nI_{rect}^n]+[k_0X+k_1X^2+\ldots k_nX^n]+$$
$$[l_0Phase+l_1Phase^2+\ldots l_nPhase^n]+A \qquad \text{(Equation 4)}$$

where

i_n, j_n, k_n, l_n, A are constants

X corresponds to a variable reactance element

Equation 4 may be used to generally determine the estimated induced voltage for any PRU **600**. However, other similar equations including other variables corresponding to a different PRU implementation may be used to generate an estimate of the induced voltage for the PRU **600**.

In some implementations, the first estimator of the controller **630** uses a look-up table estimator model. This estimator model may comprise one or more look-up tables that are generated based on simulation data or hardware prototype measurements. Accordingly, the second estimator may select the induced voltage EMF_{FB} from the look-up table(s) based on the V_{rect}, I_{rect}, and control variable inputs described herein, which may correspond to a single entry for the induced voltage EMF_{FB}. Such an implementation may utilize reduced computational power as compared to the curve fit estimator model. In some implementations, the first estimator of the controller **630** uses an analytical estimator model that is based on a description of the PRU **600**. Such an estimator model may utilize an analytical model of a component of the PRU **600** (e.g., the synchronous rectifier **620**) and a simplified equivalent model for the remaining portions of the PRU **600** (e.g., a Thevenin equivalent model for the front end of the PRU **600** when the analytical model is the synchronous rectifier **620**). Accordingly, the analytical model may comprise a physical model or a model comprising functionally equivalent equations corresponding to the components of the PRU **600**. For example, the Thevenin equivalent model may correspond to one or more components of the PRU **600** in the analytical model. This is different from the curve fit estimator described herein, which

may comprise a mathematical model based on simulated or measured data as opposed to equivalents.

Once (or while) the PRU **600** identifies or determines the estimated induced voltage EMF_{FB}, the controller **630** of the PRU **600** (e.g., via the controller **630**) may estimate and/or predict a target induced voltage EMF_{SET} at which the power transfer between the PTU and the PRU **600** will be at optimal efficiency. In some implementations, the controller **630** comprises a second estimator that is used to estimate the target induced voltage EMF_{SET} at the PRU **600**. The target induced voltage may correspond to a particular PRU **600** system state. For example, the particular system state comprises a particular position within the magnetic field or on the charging surface of the PTU **605**. In some implementations, the particular system state comprises one or more components of the PRU **600** (e.g., the current set points of the dynamically tunable impedance adjustment circuit **610** or the controlled synchronous rectifier **620**.

In some implementations, the second estimator that is used to estimate the target induced voltage EMF_{SET} comprises one or more estimation models to determine the target induced voltage EMF_{SET} based on inputs that tell the second estimator the system state(s) of the PRU **600**. A non-exhaustive list of exemplary estimation models for the second estimator is provided below.

The second estimator of the controller **630** may comprise a multi-variable curve fit estimator model based on simulation data or hardware prototype measurements. The curve fit model may generate an equation that is based on particular hardware or a component of the PRU **600** (e.g., a unique curve fit model may be generated for each "system state" of the PRU **600**). For example, the multi-variable curve fit estimator model may be based on a simulation of a dynamically tuned PRU **600** (e.g., a dynamically tuned impedance adjustment circuit **610** or a controlled synchronous rectifier **620**) having particular tuning characteristics or set point(s). In some implementations, the multi-variable curve fit estimator model includes efficiency information and/or data in its calculations.

In some implementations, the second estimator of the controller **630** uses a look-up table estimator model. This estimator model may comprise a look-up table that is generated based on simulation data or hardware prototype measurements. Accordingly, the second estimator may select the target induced voltage EMF_{SET} from the look-up table based on the V_{rect}, I_{rect}, efficiency information, and control variable inputs described herein, which may correspond to a single entry for the induced voltage EMF_{SET}. Such an implementation may utilize reduced computational power as compared to the curve fit estimator model. In some implementations, the second estimator of the controller **630** uses an analytical estimator model that is based on a description of the PRU **600**. Such an estimator model may utilize an analytical model of a component of the PRU **600** (e.g., the synchronous rectifier **620**) and a simplified equivalent model for the remaining portions of the PRU **600** (e.g., a Thevenin equivalent model for the front end of the PRU **600** when the analytical model is the synchronous rectifier **620**).

In some implementations, the second estimator of the controller **630** uses a rule based approach to determine the target induced voltage EMF_{SET}. Accordingly, the second estimator of the controller **630** may implement the rule based approach whereby a goal (e.g., a desired value) is achieved at the PRU **600** by adjusting or changing an associated variable, eliciting a corresponding adjustment or change at the PTU **605**. Accordingly, the second estimator

may use a set of rules that instruct the controller **630** to perform an action and monitor a result of that action, which should be a reduction or increase of an associated value. For example, the controller **630** may implement the rule based approach by decreasing the target induced voltage EMF_{SET}. Such a decrease in the induced voltage EMF_{SET} may result in the PTU **605** reducing its transmit current I_{tx}. The PRU controller **630** may continue to decrease the target induced voltage EMF_{SET} until the controlled synchronous rectifier **620** has a control phase of zero, which may lead to greater efficiency as compared to operating the controlled synchronous rectifier with a phase offset. Accordingly, such a rule implemented by the controller **630** may be "decrease EMF_{SET} until the phase=0" or something similar. In some implementations, the first estimator and the second estimator may be combined into a single estimator that is capable of selecting one or more estimator models dependent on the system state of the PRU **600**.

In some implementations, the PRU **600** further comprises a communication circuit. The communication circuit may be configured to communicate one or both of the estimated induced voltage EMF_{FB} and the estimated target induced voltage EMF_{SET}. In some implementations, the PTU **605** receives the two values (EMF_{FB} and EMF_{SET}) to replace an expected V_{rect} and $V_{rectset}$ (corresponding to a PRU **600** desired rectified voltage). In some implementations, the communication circuit comprises a Bluetooth or Wi-Fi module. In some implementations, the communication circuit comprises another controller or the impedance adjustment circuit **610** that communicates with the PTU **605** via inband signaling. In some implementations, the communication circuit associates the estimated induced voltage and estimated target induced voltage with legacy V_{rect} values to enable communications with legacy PTUs **605**. In some implementations, the PRU **600** communicates current values, signals (e.g., bits or flags) indicating overvoltage or other potentially harmful conditions, and similar values and/or indicators to the PTU **605** that pertain to the wireless charging relationship between the PTU **605** and the PRU **600**. FIG. **7** is a graph **700** of power losses of the PRU **600** (broken down into resonator losses—**702**, rectifier losses—**706**, and EMI filter losses—**704**) as a function of induced voltage, for a specific system state of the PRU **600**, in accordance with exemplary implementations of the invention. The graph **600** shows power losses in watts (W) on the y-axis and induced voltage in volts (V) on the x-axis.

Line **702** (corresponding to resonator losses) of graph **700** shows a power loss of approximately 0.325 W at an induced voltage of approximately 4V. Line **702** shows that the power loss decreases as the induced voltage increases until the induced voltage is between 10 and 14V. Between 10 and 14V, the power losses are roughly level at approximately 0.075 W. Above 14V, line **702** shows the power loss begins to increase as the induced voltage increases. At approximately 21V, the power loss has increased to approximately 0.11 W and continues increasing as the induced voltage increases.

Line **704** (corresponding to EMI filter losses) of graph **700** shows a power loss of approximately 0.150 W at an induced voltage of approximately 4V. Line **704** shows that the power loss due to the EMI filter generally continuously decreases as the induced voltage increases. At approximately 21V, the power loss has decreased to approximately 0.050 W and continues decreasing as the induced voltage increases.

Line **706** (corresponding to rectifier losses) of graph **700** shows a power loss of approximately 0.080 W at an induced

voltage of approximately 4V. Line **706** shows that the power loss due to the rectifier generally continuously decreases as the induced voltage increases. At approximately 21V, the power loss has decreased to approximately 0.010 W and continues decreasing as the induced voltage increases.

The graph **700** of FIG. **7** thus shows that operating at a target induced voltage EMF_{SET} may provide for reduced losses at the PRU **600** because losses due to the resonator, the rectifier, and interference can be minimized. For example, graph **700** may indicate that the target induced voltage EMF_{SET} may be between 10 and 14V, where the resonator loss (line **702**) is at its minimum value and where the rectifier losses (line **704**) and interference losses (line **706**) are close to their minimum values. For example, the target induced voltage EMFSET may correspond to a voltage within a threshold range (e.g., above and below minimum and maximum threshold values, respectively) at which combined losses due to the resonator, rectifier, and interference are within 0.1 W of their minimum values.

FIG. **8** is a flowchart includes a plurality of steps of a method **800** of estimating an induced voltage of the receiver (PRU) **600**, in accordance with exemplary implementations of the invention. For example, the method **800** could be performed by the PRU **500** illustrated in FIG. **5**. Method **800** may also be performed by the PRU **600** of FIG. **6** in some implementations. A person having ordinary skill in the art will appreciate that the method **800** may be implemented by other suitable devices and systems. Although the method **800** is described herein with reference to a particular order, in various implementations, blocks herein may be performed in a different order, or omitted, and additional blocks may be added.

The method **800** begins at operation block **805** with the PRU **600** receiving power from a magnetic field generated by a power transmitter (PTU). In some implementations, the PRU **600** may receive charging power that is then provided to a load at operation block **810**. In some implementations, the power is used to charge the load (e.g., a battery or storage cell). In some implementations, the power is used to directly power electronics of the PRU **600**.

At operation block **815**, the PRU **600** measures at least one of a rectified current and a rectified voltage at the load. In some implementations, the rectified current and the rectified voltage may be measured by a dedicated current and/or voltage measuring component (not shown). In some implementations, the rectified current and/or the rectified voltage may be measured at the rectifier, e.g., the synchronous rectifier **620**).

At operation block **820**, the PRU **600** estimates a first voltage induced by the magnetic field at the PRU **600**. In some implementations, the first voltage estimate may be based at least in part on at least one of the measured current and the measured voltage. In some implementations, the first voltage estimate may be further based at least in part on at least one operation parameter of at least one receiver component of the PRU **600**. For example, the at least one operation parameter comprises one or more of a capacitance, an inductance, a duty cycle, and a phase of the at least one receiver component (e.g., the synchronous rectifier **620** or the impedance adjustment circuit **610**) when the controller estimates the first voltage.

At operation block **825**, the PRU **600** estimates a second voltage based on at least the one operation parameter of the at least one receiver component. In some implementations, the second voltage corresponds to a voltage at which the power receiver circuit operates with an efficient level that

exceeds a threshold efficiency. In some implementations, the at least one operation parameter comprises one or more of parameters listed above

At operation block **830**, the PRU **600** communicates the first voltage and the second voltage to the power transmitter (e.g., PTU **400**). In some implementations, the PRU **600** communicates the first and second voltages to the PTU **400** via the antenna **605**. In some implementations, the antenna **605** may communicate the first and second voltages via backscatter or in-band signaling. In some implementations the antenna **605** (or another antenna of the PRU **600**, not shown) may communicate the first and second voltages to the PTU **400** via any communications means or standard (e.g., Bluetooth, Wi-Fi, near-field communication (NFC), etc.).

An apparatus for wirelessly receiving power may perform one or more of the functions of method **800**, in accordance with certain implementations described herein. The apparatus may comprise means for receiving power from a magnetic field generated by a power transmit unit. In certain implementations, the means for receiving power from a magnetic field generated by a power transmit unit can be implemented by the receive antenna **504** (FIG. **5**) or the antenna **605**. In some implementations, the means for receiving power from a magnetic field generated by a power transmit unit can be implemented by the PRU **600**. In certain implementations, the means for receiving power from a magnetic field generated by a power transmit unit can be configured to perform the functions of block **805** (FIG. **8**). The apparatus may further comprise means for providing power to a load. In certain implementations, the means for providing power to a load can be implemented by one or more receiver components of the apparatus or the PRU **600**. In certain implementations, the means for providing power to a load can be configured to perform the functions of block **810** (FIG. **8**).

The apparatus may further comprise means for measuring at least one of a current and a voltage at the load. In certain implementations, the means for measuring at least one of a current and a voltage at the load can be implemented by at least one sensor. In some implementations, the means for measuring at least one of a current and a voltage at the load can be implemented by the controller **630**. In certain implementations, the means for measuring at least one of a current and a voltage at the load can be configured to perform the functions of block **815** (FIG. **8**). The apparatus may further comprise means for estimating a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and at least one operation parameter of at least one receiver component. In certain implementations, the means for estimating the first voltage can be implemented by the controller **630** of the PRU **600**. In certain implementations, the means for estimating the first voltage can be configured to perform the functions of block **820** (FIG. **8**).

The apparatus may further comprise means for estimating a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the means for receiving power operates with an efficiency level that exceeds a threshold efficiency. In certain implementations, the means for estimating the second voltage can be implemented by the controller **630** of the PRU **600**. In certain implementations, the means for estimating the second voltage can be configured to perform the functions of block **825** (FIG. **8**). The apparatus may further comprise means for communicating the first voltage and the second voltage to

the power transmit unit. In certain implementations, the means for communicating can be implemented by the antenna **605** or a communication circuit of the PRU **600** (not shown). In certain implementations, the means for communicating can be configured to perform the functions of block **830** (FIG. **8**).

In some embodiments, an apparatus for receiving wireless power may comprise, in some implementations, the PRU **600** of FIG. **6** and the PRU **600** may perform associated functions and methods.

Information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

The various illustrative logical blocks, modules, circuits, and method steps described in connection with the implementations disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. The described functionality may be implemented in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the implementations.

The various illustrative blocks, modules, and circuits described in connection with the implementations disclosed herein may be implemented or performed with a general purpose hardware processor, a Digital Signal Processor (DSP), an Application Specified Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose hardware processor may be a microprocessor, but in the alternative, the hardware processor may be any conventional processor, controller, microcontroller, or state machine. A hardware processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

The steps of a method and functions described in connection with the implementations disclosed herein may be embodied directly in hardware, in a software module executed by a hardware processor, or in a combination of the two. If implemented in software, the functions may be stored on or transmitted as one or more instructions or code on a tangible, non-transitory computer readable medium. A software module may reside in Random Access Memory (RAM), flash memory, Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), registers, hard disk, a removable disk, a CD ROM, or any other form of storage medium known in the art. A storage medium is coupled to the hardware processor such that the hardware processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the hardware processor. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc,

digital versatile disc (DVD), floppy disk and Blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer readable media. The hardware processor and the storage medium may reside in an ASIC.

For purposes of summarizing the disclosure, certain aspects, advantages and novel features s have been described herein. It is to be understood that not necessarily all such advantages may be achieved in accordance with any particular implementation. Thus, the present disclosure may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

Various modifications of the above-described implementations will be readily apparent, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of the application. Thus, the present application is not intended to be limited to the implementations shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. An apparatus for receiving wireless power, comprising:
a power receiver circuit configured to:
    receive power from a magnetic field generated by a power transmitter, and
    provide power to a load;
at least one receiver component operating with the power receiver circuit based, at least in part, on at least one operation parameter;
at least one sensor configured to measure at least one of a current and a voltage at the load;
a controller configured to:
    estimate a first voltage induced by the magnetic field at the power receiver circuit based on the at least one measured current and measured voltage and the at least one operation parameter of the at least one receiver component, the power receiver circuit operating with a first amount of power loss when the first voltage is induced, and
    estimate a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the power receiver circuit operates with an efficiency level that exceeds a threshold efficiency and with a second amount of power loss that is less than the first amount of power loss; and
a communication circuit configured to communicate the first voltage and the second voltage to the power transmitter and cause the power transmitter to operate based on the second voltage.

2. The apparatus of claim **1**, wherein the at least one operation parameter comprises one or more of a capacitance, an inductance, a duty cycle, and a phase of the at least one receiver component when the controller estimates at least one of the first voltage and the second voltage.

3. The apparatus of claim **1**, wherein the controller is further configured to convert at least one of the estimated first voltage and the estimated second voltage to a format or value for communication to the power transmitter.

4. The apparatus of claim **1**, wherein the controller estimates at least one of the first voltage and the second voltage based at least in part on an estimator model, the estimator model including variables for a measured current,

a measured voltage, and the at least one operation parameter of the at least one receiver component.

5. The apparatus of claim 4, wherein the controller is further configured to generate the estimator model based on at least one of a simulation or a hardware prototype of the apparatus.

6. The apparatus of claim 1, wherein the controller estimates at least one of the first voltage and the second voltage based at least in part on a look-up table, the look-up table including entries for measured currents, measured voltages, and the at least one operation parameter of the at least one receiver component.

7. The apparatus of claim 6, wherein the controller is further configured to generate the look-up table based on at least one of a simulation or a hardware prototype of the apparatus.

8. The apparatus of claim 1, wherein the estimated second voltage corresponds to a voltage at which combined losses by the power receiver circuit and the at least one receiver component are below a threshold value.

9. The apparatus of claim 1, wherein the controller estimates the second voltage by, at least in part, adjusting the estimated second voltage until the at least one operation parameter of the at least one receiver component reaches a threshold value.

10. A method for receiving wireless power at a power receive unit, comprising:

receiving power, via a power receive circuit, from a magnetic field generated by a power transmit unit;

providing power to a load;

measuring at least one of a current and a voltage at the load;

estimating a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and at least one operation parameter of at least one receiver component, the power receive unit operating with a first amount of power loss when the first voltage is induced;

estimating a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the power receive circuit operates with an efficiency level that exceeds a threshold efficiency and with a second amount of power loss that is less than the first amount of power loss;

communicating the first voltage and the second voltage to the power transmit unit;

causing the power transmit unit to operate based on the second voltage.

11. The method of claim 10, wherein the at least one operation parameter comprises one or more of a capacitance, an inductance, a duty cycle, and a phase of the at least one receiver component when the at least one of the first voltage and the second voltage is estimated.

12. The method of claim 10, further comprising converting at least one of the estimated first voltage and the estimated second voltage to a format or value for communication to the power transmit unit.

13. The method of claim 10, further comprising estimating at least one of the first voltage and the second voltage based at least in part on an estimator model, the estimator model including variables for a measured current, a measured voltage, and the at least one operation parameter of the at least one receiver component.

14. The method of claim 13, further comprising generating the estimator model based on at least one of a simulation or a hardware prototype of the power receive unit.

15. The method of claim 10, further comprising estimating at least one of the first voltage and the second voltage based at least in part on a look-up table, the look-up table including entries for measured currents, measured voltages, and the at least one operation parameter of the at least one receiver component.

16. The method of claim 15, further comprising generating the look-up table based on at least one of a simulation or a hardware prototype of the power receive unit.

17. The method of claim 10, wherein the estimated second voltage corresponds to a voltage at which combined losses by the at least one receiver component is below a threshold value.

18. The method of claim 10, wherein the second voltage is estimated by, at least in part, adjusting the estimated second voltage until the at least one operation parameter of the at least one receiver component reaches a threshold value.

19. An apparatus for receiving wireless power, comprising:

means for receiving power from a magnetic field generated by a power transmit unit;

means for providing power to a load;

means for measuring at least one of a current and a voltage at the load;

means for estimating a first voltage induced by the magnetic field based on the at least one measured current and measured voltage and at least one operation parameter of at least one receiver component, the means for receiving power operating with a first amount of power loss when the first voltage is induced;

means for estimating a second voltage based on the at least one operation parameter of the at least one receiver component, the second voltage corresponding to a voltage at which the means for receiving power operates with an efficiency level that exceeds a threshold efficiency and with a second amount of power loss that is less than the first amount of power loss;

means for communicating the first voltage and the second voltage to the power transmit unit; and

means for causing the power transmit unit to operate based on the second voltage.

20. The apparatus of claim 19, wherein the at least one operation parameter comprises one or more of a capacitance, an inductance, a duty cycle, and a phase of the at least one receiver component when the at least one of the first voltage and the second voltage is estimated.

21. The apparatus of claim 19, further comprising means for converting at least one of the estimated first voltage and the estimated second voltage to a format or value for communication to the power transmit unit.

22. The apparatus of claim 19, further comprising means for estimating at least one of the first voltage and the second voltage based at least in part on an estimator model, the estimator model including variables for a measured current, a measured voltage, and the at least one operation parameter of the at least one receiver component.

23. The apparatus of claim 22, further comprising means for generating the estimator model based on at least one of a simulation or a hardware prototype of the power receive unit.

24. The apparatus of claim 19, further comprising means for estimating at least one of the first voltage and the second voltage based at least in part on a look-up table, the look-up table including entries for measured currents, measured voltages, and the at least one operation parameter of the at least one receiver component.

25. The apparatus of claim **24**, further comprising means for generating the look-up table based on at least one of a simulation or a hardware prototype of the power receive unit.

26. The apparatus of claim **19**, wherein the estimated second voltage corresponds to a voltage at which combined losses by the at least one receiver component is below a threshold value.

27. The apparatus of claim **19**, wherein the second voltage is estimated by, at least in part, adjusting the estimated second voltage until the at least one operation parameter of the at least one receiver component reaches a threshold value.

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